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TERMINAL VELOCITIES OF THE WINDS FROM RAPIDLY ROTATING OB STARS

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ABSTRACT

This paper presents measurements of terminal velocities of OB stars which are rapid rotators, based on archival high dispersion IUE spectra of the C IV resonance doublet. The terminal velocities of the most rapidly rotating stars are systematically lower than those of the less rapidly rotating stars, though the number of very rapid rotators is small. The modified line-radiation driven wind model of Friend and Abbott, which takes into account the finite size of the star as well as its rotation, predicts that the terminal velocity should indeed drop with increasing rotational velocity, in agreement with the new measurements.

Subject headings: line profiles - stars: early-type -- stars: mass loss - stars: rotation -- stars: winds - ultraviolet: spectra

I. INTRODUCTION

The theory of line-radiation driven winds, based on the model of Castor, Abbott, and Klein (1975; hereafter CAK), and recently improved by Friend and Abbott (1986; hereafter FA) and Pauldrach, Puls, and Kudritzki (1986), is now very successful in predicting mass loss rates ($\dot{M}$) and terminal velocities (v_∞) for the winds from O stars, early B stars, and B supergiants. The recent predictions of FA and Pauldrach et al. are in much closer agreement with observations than those of the original CAK model. The predicted mass loss rates have the same dependence on stellar luminosity as the observational determinations of Abbott, Bieging, and Churchwell (1981), based on radio continuum emission, and of Garmany et al. (1981), based on UV line profile fitting. They also agree to within a factor of about two in magnitude with the observational determinations. The predicted terminal velocities agree very well with UV P Cygni line measurements in both magnitude and dependence on the stellar escape velocity v_{esc} (except for the stars with very high escape velocities; see FA). Because of the different dependence of the terminal velocity on the CAK radiation force parameters, even the decrease in the ratio of v_∞/v_{esc} for the late B supergiants can now be explained.

The cause of this better agreement is the improved treatment of the source of continuum radiation which is the driving force behind the wind. Instead of assuming it to be a point source, as in CAK, the new models use the approximation that the source of radiation is a uniform disk. The main effect of this assumption is to reduce the line radiation force near the star, since the radiation field is no longer purely radial, and not all of the momentum of the radiation field is added to the flow. This effect reduces the mass loss rate, and, since less mass is being accelerated by the same force at large radii where the point source approximation is good, the terminal velocity increases. Both of these changes are in the right direction and of the right size to explain the observations of hot star winds.

Since we can now confidently predict the properties of the winds from "normal" OB stars within roughly the observational uncertainty, we are in a position to investigate secondary effects on the acceleration of the winds. Another important property of OB stars is that they are rapid rotators (Conti and Ebbets 1977). Different rotational velocities could possibly explain some of the remaining scatter in the observational data. There have already been attempts to model the effects of rotation on the properties of the winds. Castor (1979) included the effects of rotation in a one-dimensional model by considering the equatorial plane only. He found that the terminal velocity decreases with increasing rotational velocity. This dependence can be understood as the effect of a reduction in the effective escape speed on the equator, since the terminal velocity in radiation-driven winds is nearly proportional to the escape velocity (Abbott 1978; FA). With the point source approximation of CAK, Castor found that the mass loss rate was basically unchanged by rotation, since the critical point in the wind, where the mass loss rate is determined, moves outward as the rotational velocity increases. When the finite size of the star is included, as in the FA model, the mass loss rate increases with increasing rotational velocity, since the critical point is constrained by the finite disk factor to be much closer to the stellar surface. This effect can decrease the terminal velocity even more, because v_∞ will go down as the amount of mass being accelerated in the wind goes up. The FA model thus makes specific quantitative predictions for the effects of rotation on the winds from hot stars.

There have been many observational determinations of the mass loss rates and terminal velocities in hot star winds. Ultraviolet P Cygni profiles are the most useful diagnostics. The strongest P Cygni lines in the winds from hot stars are the resonance doublets of C IV and N V, accessible with the short wavelength camera (SWP) on the *International Ultraviolet Explorer* (IUE) satellite. In a typical O star wind, the short wavelength edge of the N V line is blended with Lyman α, but the short wavelength edge of the absorption component of the C IV line gives a reliable estimate (to within roughly 20%) of the terminal velocity. Mass loss rates can be estimated by fitting UV line profiles to theoretical profiles, or, if the wind is dense enough, by radio continuum emission, assuming it is free-free emission in the wind. Both of these methods, especially the line fitting method, are model-dependent, so the observational uncertainty in the mass loss rates is considerably higher than that in the terminal velocities. Our best hope for testing the predictions of the rotating wind model of FA is to look at terminal velocities of rapidly rotating stars.

The catalog of Uesugi and Fukuda (1982) contains measurements of the projected rotational velocities (v sin i) of thousands of stars, normalized to the same scale. Comparing the previous IUE measurements of terminal velocities by Cassinelli and Abbott (1981), Garmany *et al*. (1981), Olson and Castor (1981), and Garmany and Conti (1984) with the measurements in Uesugi and Fukuda, shows that not many rapid rotators have had their terminal velocities measured. In fact, only one star with a tabulated v_∞ has a rotational velocity larger than half of the critical rotational velocity, at which the centrifugal force just balances gravity. For the present study I searched the IUE archives for stars which are rapid rotators according to Uesugi and Fukuda, but which did not have published terminal velocities.

In section II I present new observational determinations of terminal velocities for 17 rapidly rotating stars, based on the short wavelength edge of the C IV resonance doublet in high dispersion IUE spectra. In section III these observations are compared to the theoretical predictions of FA. Conclusions are drawn and suggestions for further work in this area are discussed in the final section.

II. IUE MEASUREMENTS OF TERMINAL VELOCITIES

There are many early-type stars in the catalog of Uesugi and Fukuda (1982) which are rapid rotators, but only those stars which have dense enough winds will have C IV absorption extending all the way to terminal velocity. The reason that not many rapid rotators have had their terminal velocities measured in the past is that the stars with the strongest winds are the supergiants which have spun down appreciably due to angular momentum loss in their winds (see MacGregor, Friend, and Gilliland 1987). However, a class of stars which contains rapid rotators and which have strong enough winds that their terminal velocities can be measured are the B0 giants. I found several rapid rotators in this class, as well as several rapidly rotating O stars, which did not have published terminal velocities.

I searched the IUE archives for stars which met the following four criteria: 1) They had to be rapid rotators, which I took to mean that their measured projected rotational velocities (from Uesugi and Fukuda 1982) were larger than 1/3 of the critical rotational velocity. 2) They must have been observed with the IUE short wavelength camera in the high dispersion mode. 3) They had to have strong enough winds that their terminal velocities could be reliably determined from the short wavelength edge of the C IV resonance doublet. From a preliminary study of a sample of IUE C IV profiles, I determined that this would include essentially all O stars, B0 stars of luminosity class III or brighter, B1 stars of luminosity class II or brighter, and all supergiants. 4) They must not have already had a reliable terminal velocity measurement in the literature.

I found 17 stars which met these four criteria, and they are listed in Table 1. Column 1 gives the HD number of each star, and column 2 gives a spectral type and luminosity class. The sources of these spectral classifications are given in the third column. To find the critical rotational velocity for each star, and also the escape velocity with which we want to compare the terminal velocity, we need to estimate the luminosity, mass, and radius of each star. These quantities, and the observational data needed to calculate them, are given in columns 4 through 10. Absolute visual magnitudes are given in column 4, and the sources of these in column 5. Four of these stars are in clusters, so there is a very good estimate for M_v. Most, however, are field stars, for which absolute visual magnitudes were taken from the calibrations of Conti et al. (1983) for O stars and Underhill and Doazan (1982) for B stars. The effective temperatures and bolometric corrections are given in columns 6 and 7, taken from the calibration of Flower (1977). The luminosities implied from these data are given in column 8, and radii, from the definition of effective temperature, are given in column 9. Masses were taken from the evolutionary tracks of Doom (1982a, b), which contain mass loss and convective overshooting, and are shown in column 10. The resultant escape velocities are given in column 11; they are calculated from

$$v_{esc} = \sqrt{\frac{2GM(1-\Gamma)}{R}} \quad ,$$

where Γ is the ratio of the luminosity to the Eddington luminosity:

$$\Gamma = \frac{\sigma_e L}{4\pi GMc} \quad .$$

The quantity σ_e is the electron scattering opacity, and the other symbols have their usual meanings. Note that the critical rotational velocity is just $1/\sqrt{2}$ times the escape velocity.

The uncertainties in these computed escape velocities are substantial, but difficult to estimate, since the uncertainties in the "observed" quantities are difficult to estimate. In most cases the escape velocity is derived from the observed spectral type and luminosity class alone. Assuming a 10% uncertainty in T_{eff}, an uncertainty in BC and M_v of 0.5 magnitude, and an uncertainty in M of 50% (these estimates are from Conti 1984), leads to an uncertainty in the escape velocity of about 30%.

The measured terminal velocities from the IUE C IV profiles are given in column 12 of Table 1, and the ratio of these to the escape velocities are shown in column 14. The ratio v_∞/v_{esc} clusters around the value 3.0 for O and early B stars in general (Abbott 1978). We see that there is a wide range in this ratio for our sample of rapidly rotating stars, ranging from 1.3 to 4.0. This range is typical of the scatter in larger samples of early-type stars, such as in Abbott (1978). Typical examples of the C IV profiles used to estimate v_∞ are shown in Figure 1. The uncertainty in the measured terminal velocity is on the order of 20% or less, so that the uncertainty in the ratio v_∞/v_{esc} is on the order of 35%.

The last quantity given in Table 1 is the projected rotational velocity from Uesugi and Fukuda (1982), in column 13, along with the ratio of this to the critical rotational velocity in column 15. The rotational velocity ratios range from 0.37 to

0.85. It is extremely difficult to evaluate the uncertainties in the rotational velocities of Uesugi and Fukuda, since these values were obtained from many different sources, and the technique of estimating v sin i varies from source to source. Slettebak (1982) estimates that the uncertainty in v sin i for hot stars is at least 10%, and probably larger, so that the uncertainty in the rotational velocity ratio in column 15 is of the same order as the uncertainty in the ratio v_∞/v_{esc}.

Figure 2 is a plot of the ratio v_∞/v_{esc} against the ratio v sin i/v_{crit} for 16 of the stars in Table 1, along with many previous determinations for less rapidly rotating stars, shown as open circles (the other symbols will be discussed shortly). The earlier determinations were already plotted in Figure 3 of FA: without the rapid rotators, there is no clear relation between the two quantities plotted. With the inclusion of the stars from Table 1, however, there is a clear drop in v_∞/v_{esc} for the most rapidly rotating stars. To make this drop more visible, I have binned the observations by rotational velocity, and plotted the average values as filled circles, with the error bars representing the scatter (one standard deviation) within each bin. In the previous section I estimated that the uncertainty in the measured value of v_∞/v_{esc} is about 35%, so this observational uncertainty is a bit larger than the scatter error bars shown. There are only three stars in the highest rotational velocity bin, but the scatter in this bin is not very large. Note from Table 1 that these three stars range in spectral type only from B0 to B1 and in luminosity class from III to Ib, so they are a fairly homogeneous group in their observed properties, including rotational velocity.

Though there is considerable scatter in the observational determinations of v_∞/v_{esc}, the decline of terminal velocity with rotational velocity is statistically significant. The line in Figure 2 is a linear least squares fit to the data with $v \sin i/v_{crit} > 0.15$ (the few stars with smaller values of $v \sin i/v_{crit}$ exhibit a sharp systematic drop in v_∞/v_{esc} which cannot be explained by the FA model, so they were not included in the fit). This line is described by

$$\frac{v_\infty}{v_{esc}} = 3.52 \pm 0.15 - (1.43 \pm 0.40)\frac{v \sin i}{v_{crit}} \quad ;$$

the negative slope is real up to 3 1/2 standard deviations from the mean. I also found the linear correlation coefficient to be -0.428, which, for the number of data points in this sample, indicates a probability of correlation of approximately 99.9% (Young 1962).

III. COMPARISON TO MODEL PREDICTIONS

In Figure 3 I have plotted the theoretical values of v_∞/v_{esc} vs. v_{rot}/v_{crit} from the model of FA, shown as x's. The binned observations are also plotted for comparison. These theoretical values represent a range of escape velocities, which explains the scatter in v_∞/v_{esc} for a given v_{rot}/v_{crit}. The CAK radiation force parameters k and α were chosen to be those appropriate for

O and early B stars, according to the tabulations of Abbott (1982). The trend of decreasing v_∞/v_{esc} with increasing rotational velocity is evident, and it even agrees fairly well in magnitude with the observations. A linear least squares fit to the theoretical data yields

$$\frac{v_\infty}{v_{esc}} = 3.33 \pm 0.06 - (1.41 \pm 0.16) \frac{v_{rot}}{v_{crit}} ,$$

though a better fit can be obtained with a power law in $(1 - v_{rot}/v_{crit})$. Note that the slope of this line is nearly identical to that of the observational data.

Three further things should be noted about Figures 2 and 3. The first is that not all the observational determinations from FA nor from Table 1 are plotted. This is because there are systematic trends between v_∞/v_{esc} and v_{esc} which we need to eliminate in order to test for a correlation with rotational velocity. The stars with the lowest values of v_{esc}, namely the late B supergiants, have lower values for v_∞/v_{esc} because of a lower value for the radiation force parameter α (a large number of relatively optically thin lines drives the flow in these stars; see FA). So all stars with v_{esc} less than 400 km s^{-1} were dropped from Figure 2. The stars with the highest values of v_{esc}, namely the mid to late O main sequence stars, also have systematically lower values for v_∞/v_{esc} (see FA, Figures 7 and 8), a fact which cannot be explained by the model. So stars with v_{esc} greater than 1050 km s^{-1} were also eliminated from Figure 2, which includes one of the rapid rotators in Table 1.

The second thing to note about Figure 2 is that even with the elimination of the late B supergiants, which would fall in the lower left portion of the plot, the terminal velocity ratio is lower for the stars with the lowest values of projected rotational velocity. This effect is not explained by the theory, and, if it is real, may be related to a third point: the observations give only the projected rotational velocity while the theoretical models are computed for the equatorial rotational velocity. This projection effect could lower the average value of v_∞/v_{esc} for a low value of $v \sin i/v_{crit}$, since some of the stars with low projected rotational velocities actually have larger rotational velocities and, hence, will have lower terminal velocities. However, the terminal velocity is lowered by rotation predominantly on the equator, and the terminal velocities of stars seen near the pole-on orientation will likely be independent of rotation rate. We need to investigate two-dimensional models of rotating winds before we can tell how the terminal velocity actually varies with latitude. Poe (1987) is currently carrying out such an investigation.

IV. CONCLUSIONS

The new determinations of terminal velocities for rapidly rotating stars are suggestive that the ratio v_∞/v_{esc} decreases with increasing rotational velocity. Comparison to the rotating wind model of FA suggets that the model describes the terminal velocities of rapidly rotating stars fairly well. Even with the large uncertainties in the observational data, the differences in v_∞/v_{esc} between the highest bin and the lowest bin appear to be significant.

The biggest problem with making any definitive conclusions from these data is that there are only three stars which fall in the highest rotational velocity bin. It would be very desirable to find more rapidly rotating OB stars to fill out the high rotational velocity end of Figure 2. However, it will be very difficult to find many more rapid rotators that have not already been observed with IUE, as there are now probably very few Galactic OB stars that have not been observed, and very few of them would be rapid rotators.

The rotating wind model of FA also predicts that mass loss rates for the most rapid rotators will be higher than for the slow rotators. It would be interesting to calculate mass loss rates for the rapid rotators in this sample to compare to the predictions. However, there are two serious obstacles to undertaking this study. The first is that mass loss rates determined by UV profile fitting, which is the method that must be used for stars with moderate mass loss rates, are very uncertain, probably only accurate to a factor of about two. Since the rise in M for the most rapidly rotating stars in our study is predicted to be a factor of about two (see Figure 4 of FA), the effect in M will only be marginally detectable.

The second obstacle is that the line profile fitting program available at the IUE Regional Data Analysis Facilities assumes spherical symmetry. The winds from rapidly rotating stars will certainly not be spherically symmetric, since the equatorial properties will be significantly modified by rotation. It is probably a good approximation, though, to assume that the winds are axially symmetric. P. B. Kunasz (1984; private communication) has recently written a formal solution code for the calculation of line profiles in axially symmetric geometry. I am planning to use this code, in conjunction with escape probability methods to find line source functions, to calculate line profiles for rapidly rotating stars. The equator-to-pole variation of the wind properties can be calculated using the two-dimensional rotating wind model being developed by Poe (1987). I can then compare mass loss rates deduced from these profiles to those computed for the rapidly rotating stars in this sample to see if anything can be learned about the mass loss rates of rapid rotators. Note that Vardya (1985) has claimed to find correlations between certain functions of mass loss rate and rotational velocity, but his results are of marginal statistical significance.

I would like to thank Terry Armitage and Katy Garmany for teaching me how to use the IUE Regional Data Analysis Facility in Boulder. Derck Massa and Clint Poe deserve thanks for helping write the IUE archival proposal and for helping tabulate the data on the program stars. Dave Abbott and Joe Cassinelli are thanked for critical comments on the presentation of the data. This study was supported by NASA grant NAG 5-804 to the University of Wisconsin.

TABLE 1

PROGRAM STARS

HD	Sp. Type	Source	M_v	Source	T_{eff}[10] (10^3 K)	BC[10]	L ($10^4 L_o$)	R (R_o)	M[11] (M_o)	V_{esc} (km/s)	V_∞ (km/s)	Vsini[12] (km/s)	$\frac{V_\infty}{V_{esc}}$	$\frac{V\sin i}{V_{crit}}$
15642	BO III	1	-4.4	2	27	-2.6	4.9	10	15	720	1950	320	2.7	0.63
28446	BO III	3	-4.8	9	27	-2.6	7.1	12	17	700	1680	275	2.4	0.56
69106	05 Ve	1	-5.2	4	41	-3.8	31	11	42	1100	1450	320	1.3	0.41
74753	BO III	5	-4.8	9	27	-2.6	7.1	12	17	700	1230	375	1.8	0.76
88115	BO III	6	-4.8	9	27	-2.6	7.1	12	17	700	1250	245	1.8	0.50
90087	09.5 V	7	-4.0	4	33	-3.3	6.4	7.8	23	1030	2210	290	2.2	0.40
92554	09 II	6	-5.7	4	33	-3.1	26	16	29	750	1710	255	2.3	0.48
101205	07 III	1	-6.0	1	36	-3.4	45	17	40	810	3220	345	4.0	0.60
101436	06.5 V	1	-5.4	2	37	-3.5	28	13	34	900	3280	285	3.7	0.45
124314	06 V((f))	1	-5.1	4	39	-3.5	21	10	34	1050	3470	270	3.3	0.37
157246	B1 Ib	5	-5.5	9	20	-1.7	5.9	20	14	490	1190	285	2.4	0.82
165174	BO III	3	-4.8	9	27	-2.6	7.1	12	17	700	1750	290	2.5	0.59
175754	08 III((f))	8	-5.1	4	34	-3.2	16	12	26	860	2590	220	3.0	0.36
175876	06.5III(f)	1	-5.7	4	37	-3.4	34	14	37	890	3330	265	3.8	0.42
184915	BO.5 III	3	-4.8	9	25	-2.2	4.9	12	15	670	1460	270	2.2	0.57
188439	BO.5 III	3	-4.8	9	25	-2.2	4.9	12	15	670	1310	400	2.0	0.85
203064 (68 Cyg)	08 V	8	-5.5	2	36	-3.5	31	14	34	850	3230	315	3.8	0.53

SOURCES

1) Walborn 1973 (and references therein)
2) Humphreys 1978
3) Lesh 1968
4) Conti *et al.* 1983
5) Lesh 1972
6) IUE merged log
7) Balona 1975
8) Conti and Leep 1974
9) Underhill and Doazan 1982
10) Flower 1977
11) Doom 1982a,b
12) Uesugi and Fukuda 1982

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FIGURE CAPTIONS

Fig. 1.--Actual tracings of the IUE SWP images of the region around the C IV resonance doublet near 1550 Å for two stars. a) HD 188439 (B0.5 III), a very rapid rotator which has a low terminal velocity of 1310 km s^{-1}. b) HD 101436 (O6.5 V), a relatively slow rotator with a high terminal velocity of 3280 km s^{-1}.

Fig. 2.--The ratio of the terminal velocity to the escape velocity plotted against the ratio of the rotational velocity to the critical rotational velocity. The open circles are the observations (these are projected rotational velocities), and the filled circles are the observations binned according to rotational velocity, with the error bars representing the scatter (one standard deviation) within each bin. The line is a linear least squares fit to the data.

Fig. 3.--The theoretical values for the same ratios that were plotted in Figure 2, as x's, along with the binned observations from Figure 2.

Figure 1

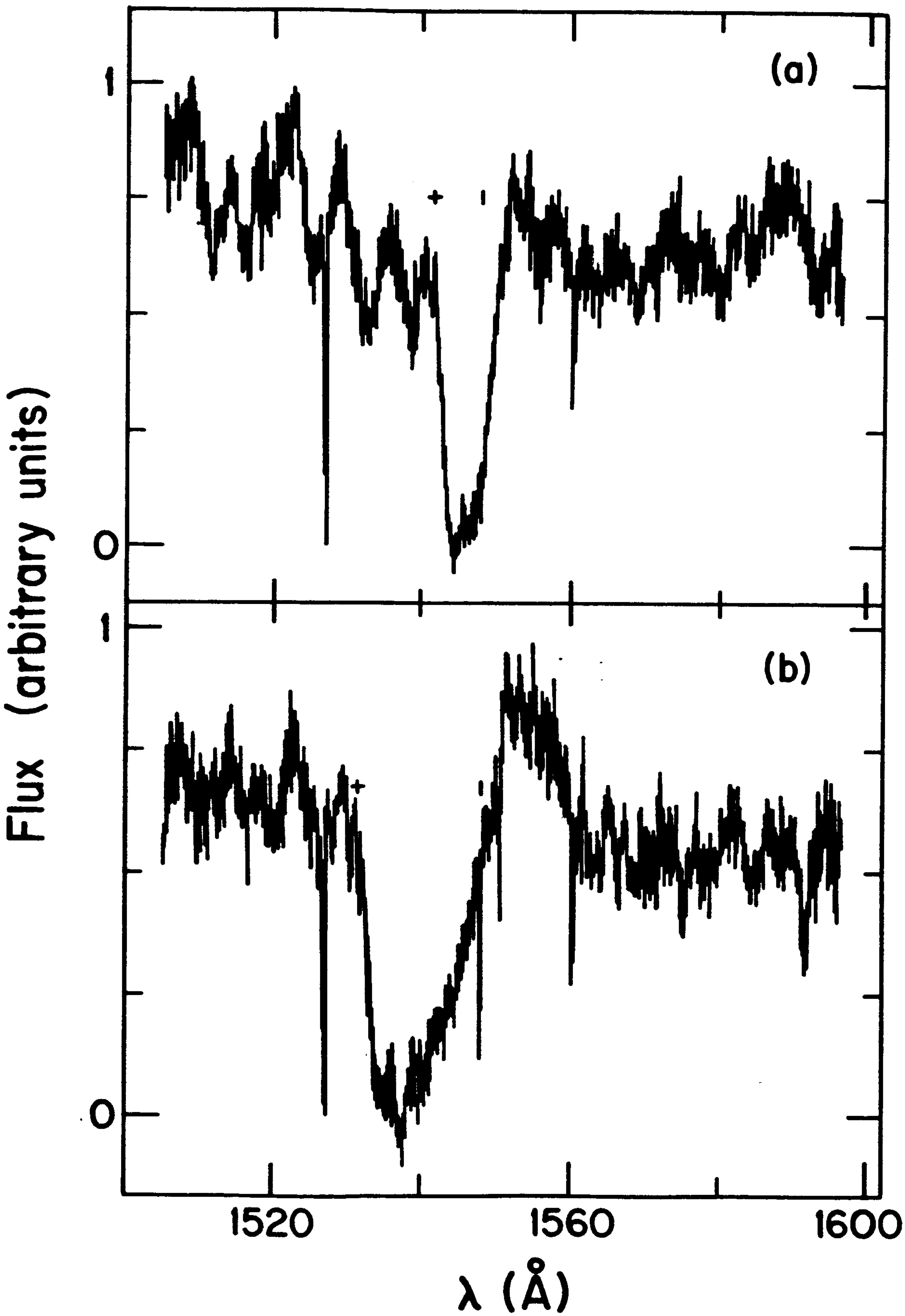

Figure 2

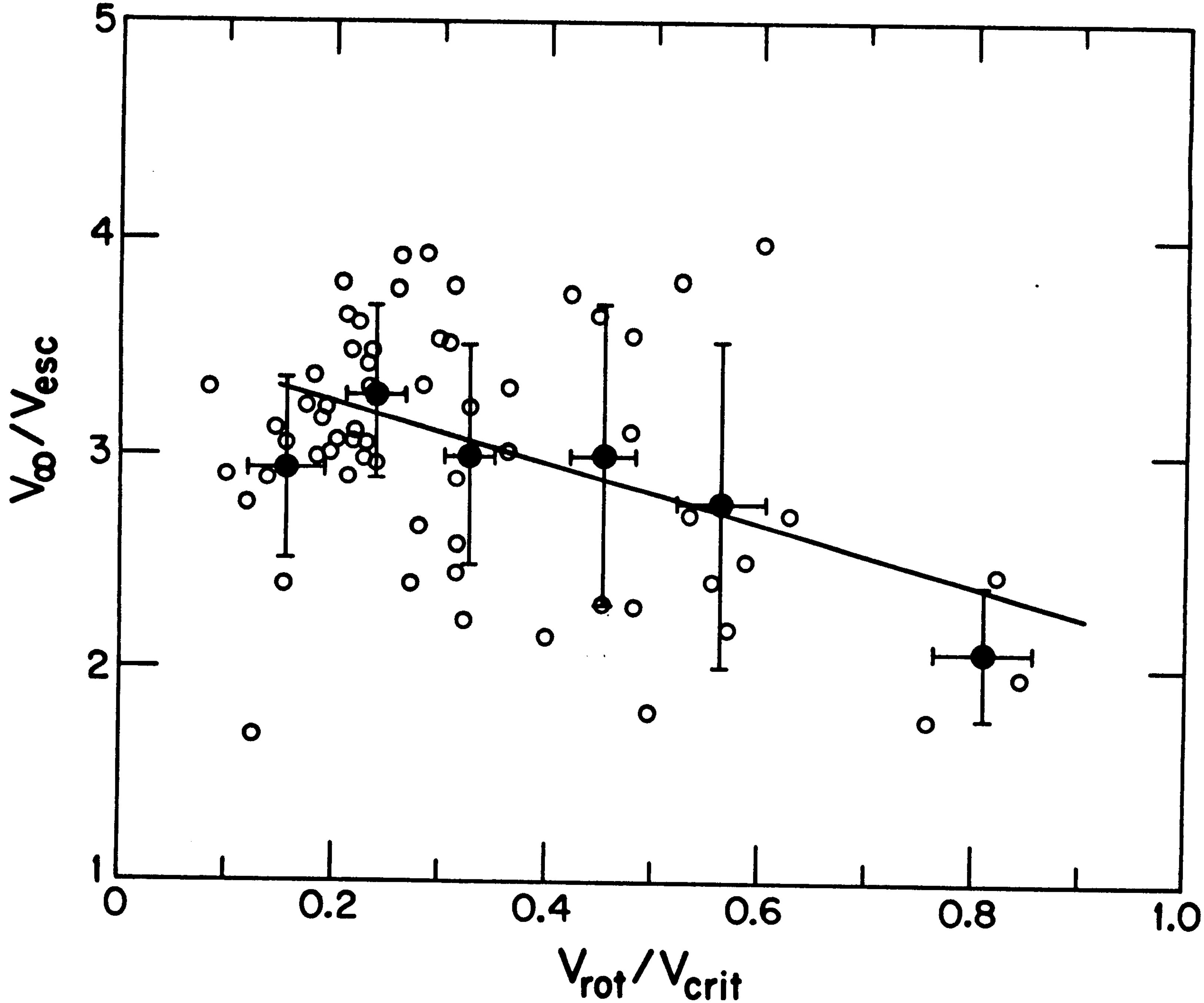

Figure 3